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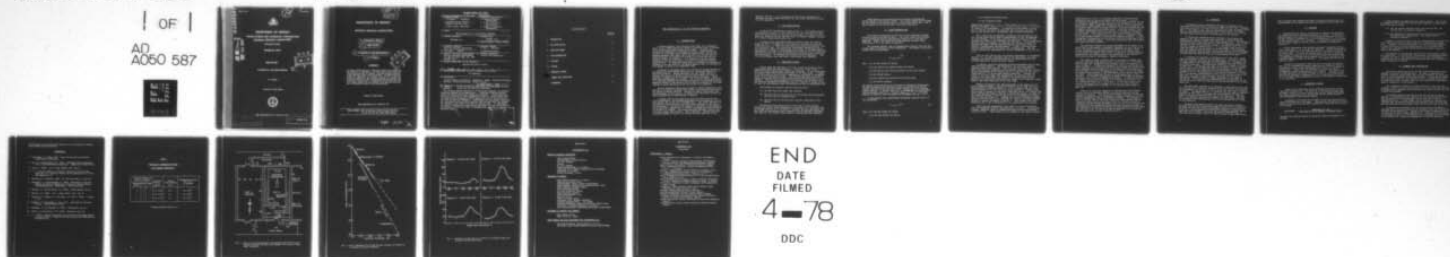
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MRL-TN-387

THE SHIELDING OF A 14 MeV NEUTRON GENERATOR

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SUMMARY

The concrete masonry shield for a 14 MeV neutron generator was designed using data supplied by the manufacturer. Subsequent radiation surveys outside the shield showed doses higher than expected. Calculations indicated the sensitivity of dose transmission factors to concrete composition. The observed dose transmission factor agreed with that of Broerse but not with that of Hacke and Prudhomme. Measurements and calculations delineated the contribution that neutrons, scattered from the upper wall that supports the laboratory roof, made to the dose in adjoining areas. In redesigning the shield a compromise was made between additional cost and restrictions on the generator's duty cycle, which is automatically controlled to ensure personnel safety.

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POSTAL ADDRESS: Chief Superintendent, Materials Research Laboratories,
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THE SHIELDING OF A 14 MeV NEUTRON GENERATOR

1. INTRODUCTION

A neutron generator, Texas Nuclear Series 9900, with a maximum 4π output of 10^{11} 14-MeV neutrons per second is installed in Bay 5, Building 694 of the Materials Research Laboratories (MRL). To comply with International Commission on Radiological Protection (ICRP) regulations, personnel in the vicinity of the generator should receive less than the maximum permissible dose (MPD), set at 100 mrem for a 40 hour week for radiation workers (2.5 mrem/h) and 10 mrem for a 40 hour week for non-radiation workers (0.25 mrem/h). It is desirable to design radiation shielding so that the above hourly rates are not exceeded in normally occupied areas. In areas where these values are exceeded the occupancy by personnel or the duty period of the neutron generator must be restricted to avoid dosage in excess of the permissible limit.

The object of shielding design is to provide the maximum shielding at the minimum cost while taking into account any constraints imposed by a practical situation. Neutron generators are such intense sources of neutrons that the use of distance, and the inverse-square law, alone is generally an impractical way of reducing the dose to personnel. Hence, additional shielding must be provided. Also, from the figures given above, it is obviously desirable for non-radiation workers to be excluded from the immediate vicinity of the shield so as to reduce the thickness of the shield required or avoid limitations on the duty period of the generator.

Neutron attenuation takes place through the energy degradation of fast neutrons by inelastic scattering and/or elastic scattering and then finally the capture of thermal neutrons. Shields are commonly constructed from concrete because it has a mixture of elements that effectively utilises all three processes and is cheap and easy to install.

Although 14-MeV neutron generators have been widely used for fast-neutron experiments, the shielding requirements for such generators are not well defined, due to the lack of reliable data. This report describes the shielding of a Texas Nuclear Series 9900 neutron generator by the use of concrete masonry. The shield was designed, on the basis of data published by the generator's manufacturer, to reduce the maximum dose-rate outside of the shield to 2.5 mrem/h. But actual dose-rates measured outside of the shield were larger than expected. After "skyshine" - neutrons that were scattered downward by the air, the roof and the thin upper part of the

generator room wall - was investigated the shield was redesigned and a compromise was made between additional cost and certain restrictions on the use of the generator.

2. THE INSTALLATION

A plan of the installation is shown in Fig. 1. The original walls of the generator room are 0.3 m thick solid brick at the north and south ends and 0.45 m thick concrete on the east and west sides, to a height of 3.65 m. Above that height on the east and west sides are thinner triangular sections, 0.22 m thick, supporting the gable roof.

To keep an open experimental geometry concrete blocks were stacked around the walls to a height of 3.65 m, except at the south end where the height was 2.3 m. A simple maze was constructed between the generator room and the control room. The total shield thicknesses, indicated in Fig. 1, were expected to reduce the maximum dose rate outside the shielding walls to approximately 2.5 mrem/h, for the maximum rated output of the 10^{11} neutrons/s, except at the north end of the building where the storeroom and corridor are used infrequently. No shielding was installed above the generator. Thus the dose in adjacent bays could have a contribution from "skyshine".

3. RADIATION SURVEY

Neutron doses were measured at 36 points around the building, using a Texas Nuclear Model 9140 Nemo Dosimeter. The neutron output of the generator and the deuteron beam current were monitored. It was assumed that the neutron output was linearly proportional to the beam current. A sample of the dose rates is shown in Fig. 1 normalised to correspond to the maximum output of 10^{11} neutrons per second. Day and Mullender² give the neutron energy distribution after a 14-MeV neutron beam has passed through 1.3 m of concrete. From the energy response of the dosimeter, and the thick-tissue RBE (relative biological effectiveness) dose as a function of energy, it can be shown that the dosimeter would over-estimate the dose by approximately 10%.

Three things were apparent from the radiation survey :

- (a) The dose rates were higher than expected.
- (b) The dose rates at the north end of the building were unacceptable even with the low occupancy factor.
- (c) The entry point to the generator room was a weak point in the shield.

The high dose rates could be due to the action of three factors: firstly, the concrete blocks supplied were less dense ($2.0 \times 10^3 \text{ kg/m}^3$) than the average concrete ($2.3 \times 10^3 \text{ kg/m}^3$); secondly, and more importantly, the data used² indicated greater dose attenuation than is apparently achievable with concrete; and thirdly, there could be a contribution from "skyshine".

Gamma radiation is produced by neutron inelastic scattering and neutron capture in the concrete shield. But a survey showed that the gamma-ray dose outside the shield was only 10 to 20% of the neutron dose; thus it may be ignored, as the neutron dose is the controlling factor.

4. DOSE TRANSMISSION

The problem of obtaining reliable data on dose transmission through concrete is well illustrated by Fig. 2. For thick shields the difference in the transmission factors from different sources is up to an order of magnitude. Indeed, the collection of data published by Hacke³ shows differences of up to two orders of magnitude.

Two different methods, that are mathematically similar, have been used to make simple calculations of dose transmission. The removal cross section method⁴ uses the relationship

$$D = \phi_0 q B e^{-\Sigma_R x} \quad (1)$$

where D is the dose behind the shield,

ϕ_0 is the neutron flux density without the shield,

q is the dose per unit flux for neutrons of the source energy,

B is the buildup factor,

Σ_R is the removal cross section for 14 MeV neutrons,

x is the shield thickness.

The removal cross-sections may be calculated or determined experimentally. The main difficulty with the method is that the buildup factor and the removal cross-section may vary with shield thickness due to the changing neutron spectrum. A buildup factor of 5 is recommended⁴ for shield thicknesses of greater than 0.2 m. Cloutier⁵ gives $\Sigma_R = 7.5 \text{ m}^{-1}$ for 14-MeV neutrons on concrete, while Nachtigall and Heinzelman⁶ give $\Sigma_R = 8.4 \text{ m}^{-1}$.

A second method uses experimentally-determined constants C and λ in the relationship

$$D = D_0 C e^{-x/\lambda} \quad (2)$$

where D is the dose behind the shield,

D_0 is the dose without the shield,

C is a constant scattering factor,

λ is the relaxation length.

Broerse gives values of $C = 1.2$, $\lambda = 0.197 \text{ m}^7$ and $C = 2.3$, $\lambda = 0.17 \text{ m}^{8,9}$; Marshall and Knight¹⁰ give $C = 1.0$, $\lambda = 0.151 \text{ m}$, Hacke³ gives $\lambda = 0.15 \text{ m}$ for the region of his measurements. In comparing the two methods it is not easy to separate the effects of absorption and scattering, especially if data are not obtained for a considerable range of shield thicknesses.

Fig. 2 shows that the published transmission factors appear to fall into two main groups which differ by approximately an order of magnitude for thick shields. In the first group the results of Broerse^{7,8,9} and Sauermann and Schafer¹¹ are consistent with each other. In the second group the curve given by Prudhomme¹ is consistent with the data of Hacke³ and Marshall and Knight¹⁰ and also with the removal cross-section values of Cloutier⁵, and Nachtigall and Heinzelmann⁶. In Fig. 2 and solid lines represent measurements and the dashed lines extrapolations. The open circles represent our measurements for concrete thicknesses of 0.8, 1.2 and 1.3 m.

There are many factors that can influence measurements of transmission factors, e.g., the type of geometry used for the measurement, the shield thickness, the detector characteristics and the characteristics of the concrete-composition, density and water content.

To simulate a practical shielding situation measurements must be made using broad-beam geometry. The measurements that have been reported generally satisfy this condition. But it is not easy to quantify the effect that different geometries used by different authors has had. Broerse has made measurements in the range 0.0-0.33 m⁷, and 0.64-0.96 m^{8,9} and a single point at 1.3 m using three different geometries. Although the results in the first range, when extrapolated, are consistent with the results in the second range, the results in the second range are best described by postulating a scattering factor larger, and a relaxation length smaller, than those postulated for the first range.

Marshall and Knight¹⁰ have made measurements in the range 0.4-1.0 m using a geometry similar to that used by Broerse⁷ in the range 0.0-0.33 m. They postulated a relaxation length ($\lambda = 0.151 \text{ m}$) smaller than that postulated by Broerse^{8,9} ($\lambda = 0.17 \text{ m}$) in the range 0.64-0.96 m. However, they did not find it necessary to postulate a scattering factor (i.e. greater than unity) although scattering is expected on theoretical grounds, is evident in the results of Broerse^{7,8,9} and is also evident in the Monte-Carlo calculations of Allen and Futterer¹². Although the results of Marshall and Knight and those of Broerse are clearly different for concrete they obtain similar results for neutron attenuation in water^{9,10}. This suggests that their differences may be due to differences in the composition of the concrete.

Hacke³ has made measurements in the range 1.3-1.6 m by varying the angle of transmission through a shielding wall 1.3 m thick. He postulated a similar relaxation length to Marshall and Knight but did not postulate a scattering factor. There appears to be an anomaly in the results of Hacke.

Substitution of $C = 1.0$, $\lambda = 0.15$ m into expression 2 indicates larger transmission factors than were actually observed by Hacke. This is surprising as his assumption that there is no scattering correction and that the relaxation length is constant through the full thickness of the shield should tend to under-estimate the transmission factor, not over-estimate it. The geometry used by Hacke³ has been criticised by Broerse⁸ because its lack of symmetry would perturb the buildup factor. Allen and Futterer¹² have calculated transmission factors as a function of the angle of incidence of a neutron beam. Their results indicate that for thin shields the transmission factor for an inclined beam is greater than the transmission factor for a beam incident normally on a shield of equivalent thickness. If this finding may be extrapolated to thick shields, then Hacke would tend to over-estimate the relaxation length. This would increase the difference between his results and those of Broerse.

The differences between the various measurements do not appear to be reconcilable on the grounds of experimental geometry, but may be due to the effect of variations of concrete density, composition and water content. As such variations are more easily studied by use of the removal cross-section method⁴-the removal cross-section is obtained by a density-weighted summation over the cross-sections of the constituents of the concrete - this method was used to investigate a number of variations.

The results in Table 1 indicate that for concretes of similar composition a decrease of the density from 2.4×10^3 kg/m³ to 2.3×10^3 kg/m³ would increase the transmission factor through, say, 1.3 m of concrete by a factor of about 2. If more sand (assumed to be silicon dioxide) and less gravel (assumed to be calcium carbonate) was used to make the concrete, then the transmission factor through 1.3 m of concrete would be increased (by a factor of about 4 for the two examples given in Table 1) due to the change in composition and also due to the lower density of the concrete made using more sand. Another important variable is the hydrogen content of the concrete. In a concrete containing 1% by weight of hydrogen, the hydrogen contributes 15% of the total removal cross-section. A variation of 15% in the removal cross-section corresponds to a variation of a factor of 5 in the transmission factor for 1.3 m concrete. If the water content of a concrete was changed by 1% by weight, as has been observed by Broerse⁸, then the transmission factor through 1.3 m of concrete would change by about 25%.

Hence it is clear that comparison of shielding data from different sources tends to be indecisive unless the chemical composition of the concrete is specified. Thus the difference between the data of Hacke and Broerse may largely be due to differences in concrete composition, but this cannot be demonstrated with the information available. If allowance is made for the fact that we have used a concrete of lower density, and consequently probably greater sand content than that of Broerse, then the transmission factors we have observed for 0.8, 1.2 and 1.3 m of concrete are consistent with the transmission factors observed by Broerse (see Fig. 2). Our transmission factors were calculated for normal penetration of the north wall (0.8 and 1.2 m - see Section 6) and the west wall (1.3 m) using the standard neutron flux to dose conversion factor⁴.

5. SKYSHINE

A preliminary survey indicated the presence of "skyshine" by an increase in dose level with an increase of height from the floor. Readings were taken at 0.15 m, 1.0 m and 1.6 m above the floor level at points across Bay 4. The change in dose rates was approximately linear with height. The dose near the floor was 15% less than at 1.0 m, while at 1.6 m it was 15% more except near the centre of the bay where it was 30% more.

To obtain more information on the "skyshine", the dosimeter was mounted at the centre of a water-tank shield with a simple cylindrical cadmium-lined collimator having a full angle opening of 40° . The collimator was rotated about a horizontal axis in a plane including the centre of the dosimeter and the neutron generator target. The relative dose rate as a function of angle is shown in Fig. 3. It was readily shown that for all cases the angle from the horizontal to the mean height of the triangular thin wall coincided with the angle from the horizontal at which the maximum dose was measured, indicating that a considerable fraction of the downward-scattered dose came from the thin part of the generator-room walls.

To quantify the proportion of "skyshine" in the total dose a simple model was proposed to simulate the shielding walls. For ease of calculation the triangular thin upper wall was approximated by a rectangular wall of height equal to the mean height of the triangular wall, and sitting on the thicker lower wall. The walls were divided into a number of sections of equal area. The dosimeter was taken to be located on a line perpendicular to the face of the shielding wall and equidistant from the ends. The shielding wall was assumed to act as uniform diffuser of the neutrons incident on it i.e. the distribution of the scattered neutrons is isotropic. This is a reasonable approximation at least for the central portion of the lower wall, as it may be seen from Fig. 3 that when the lower wall is observed the dosimeter reading is largely independent of the angle of observation. The accuracy of the approximation is less important for the ends of the wall as they contribute less to the dose because of the inverse-square law.

The solid angle subtended at the dosimeter by each section of the wall was calculated for a particular dosimeter height and distance from the wall. The experimental data obtained at 3.5 m from the wall were used to normalise the result. The angular data at 3.5 m indicate that the number of neutrons scattered per unit area of the upper wall is approximately 10 times the number of neutrons scattered per unit area of the lower wall. The total dose at the dosimeter was obtained by summing the contribution from each of the sections and normalising the total to the observed dose 3.5 m from the shielding wall.

The model could generally predict the doses observed at different distances from the wall and different heights from the floor to within 15%. But while the total dose remains approximately constant at various points across Bay 4 the percentage of the total dose apparently scattered from the upper wall varies sharply - from about 20% near the shielding wall, to about 50% near the centre of Bay 4, to about 75% near the Bay 4/Bay 3 wall.

Thus it appears that transmission factors calculated for points near the shielding wall are not greatly perturbed by scattering from the upper wall.

6. OPTIONS

Consideration was given to various ways of improving the shielding and reducing the dose to personnel outside of the walls. To decrease the high dose rates at the north end of the building the shield at the north end was increased in thickness to 1.2 m by the addition of 0.4 m of stacked concrete blocks, density $2.3 \times 10^3 \text{ kg/m}^3$. A subsequent survey showed that the dose rates outside of the wall, at the north end, had dropped by a factor of 5.

Further improvement of the shield would entail decreasing both the direct penetration of the walls and the "skyshine". Roofing the generator room was considered to be too costly and would be structurally difficult on the present site. To reduce the external dose by an order of magnitude would require the addition of 0.5 m of concrete around the interior walls, a strengthening of the maze and the addition of 0.5 m of concrete in the triangular region to reduce the "skyline". This option was ruled out as being too costly.

Instead it was decided to limit the dose to personnel in adjacent bays, not by increasing the shield thickness but by increasing the use of the generator outside normal working hours when there are no personnel in adjacent bays. Hence, only the shielding at the south end will be strengthened to give more protection to the operator. The walls at the far south end will be increased in height to 3.65 m. Both walls of the maze will be increased in thickness by 0.5 m of stacked concrete blocks ($2.3 \times 10^3 \text{ kg/m}^3$) except immediately in front of the doorway so that access is not restricted.

7. GENERATOR CONTROL

Because of the limitations of the shielding the generator clearly cannot have unlimited use. The generator is controlled to ensure that personnel outside of the walls receive less than the maximum permissible dose (MPD), arbitrarily set at 30 mrem/week for MRL radiation workers¹³ and 10 mrem/week for non-radiation workers.

A parameter Q is defined as the product of the beam current and the time of operation with a new target. This indicates the amount of use the generator can have before the MPD is exceeded at a particular point outside of the shield.

$$Q(\text{mA.h/week}) = \frac{(\text{MPD/week}) \times 2.5 \text{ mA}}{\text{Dose rate at 2.5 mA (mrem/h)} \times \text{Occupancy Factor}}$$

Naturally the limiting location is the one for which the relevant Q is a minimum.

A Nemo dosimeter is mounted near the control console. This is used in conjunction with a time clock and two preset registers to record integrated doses and to ensure :

- (a) that the operator does not receive more than the MPD - the relevant dose is recorded by Register 1;
- (b) that personnel in adjoining bays do not receive more than the MPD during normal working hours - the relevant dose is recorded by Register 2.

Register 1 records the dose at any time, while Register 2 records only if the time clock contact is closed, which it is during normal working hours. Register 1 is preset according to the ratio Q_C/Q_D and Register 2 is preset according to the ratio Q_M/Q_D where Q_C is the Q value at the console, Q_M is the minimum value of Q outside of the shield and Q_D the Q value at the dosimeter.

The generator is automatically turned off if either register reaches the present dose. In this way the "book-keeping" is automatically done as to whether the dose to the console operator or the dose to personnel in adjoining bays is the limiting factor in generator operation, and hence the safety of personnel is ensured.

8. SUMMARY AND CONCLUSIONS

The concrete masonry shield for the MRL 14 MeV neutron generator was designed on the basis of published data. But when the shield was constructed a radiation survey showed that the doses outside of the walls were about an order of magnitude greater than expected. Calculation of removal cross-sections showed that dose transmission factors through shields that are many neutron mean free paths thick are quite sensitive to variations in chemical composition or total density.

The transmission factors for concrete observed in this study, when allowance is made for the difference between the concrete used and that used by Broerse, are in agreement with the Broerse data rather than with the data of Hacke and Prudhomme.

A collimated dosimeter was used to show that the dose in the bay adjacent to the generator mainly comprised the dose penetrating the shield wall and the dose scattered downwards from the thin part of the wall supporting the roof. A simple model, used to simulate the complete wall, indicated that the downward scattered dose was about 20% of the total dose near the shield wall but increased to about 75% at the far side of the bay.

To increase the thickness of the shield walls and to add adequate shielding above the neutron generator was considered costly and structurally difficult on the present site. Instead it was decided to make more use of the generator outside of normal working hours. Consequently the shielding was increased at one end of the generator room to decrease the dose received by the operator and a system was implemented to control the generator

automatically so that neither the operator nor any personnel in adjacent bays received more than the MPD.

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TABLE 1

VARIATION OF TRANSMISSION FACTOR

WITH CONCRETE COMPOSITION

| Concrete Composition (parts by volume) | | | Concrete Density (kg/m ³) | Removal Cross Section (m ⁻¹) | Transmission Factor* for 1.3 m of Concrete |
|---|------|--------|---|--|--|
| Limestone Gravel | Sand | Cement | | | |
| 4 | 2 | 1 | 2.4×10^3 | 8.8 | 5.4×10^{-5} |
| 4 | 2 | 1 | 2.3×10^3 | 8.4 | 9.7×10^{-5} |
| 2 | 4 | 1 | 2.0×10^3 | 7.3 | 3.6×10^{-4} |

* Assumes Build-up Factor of 5.

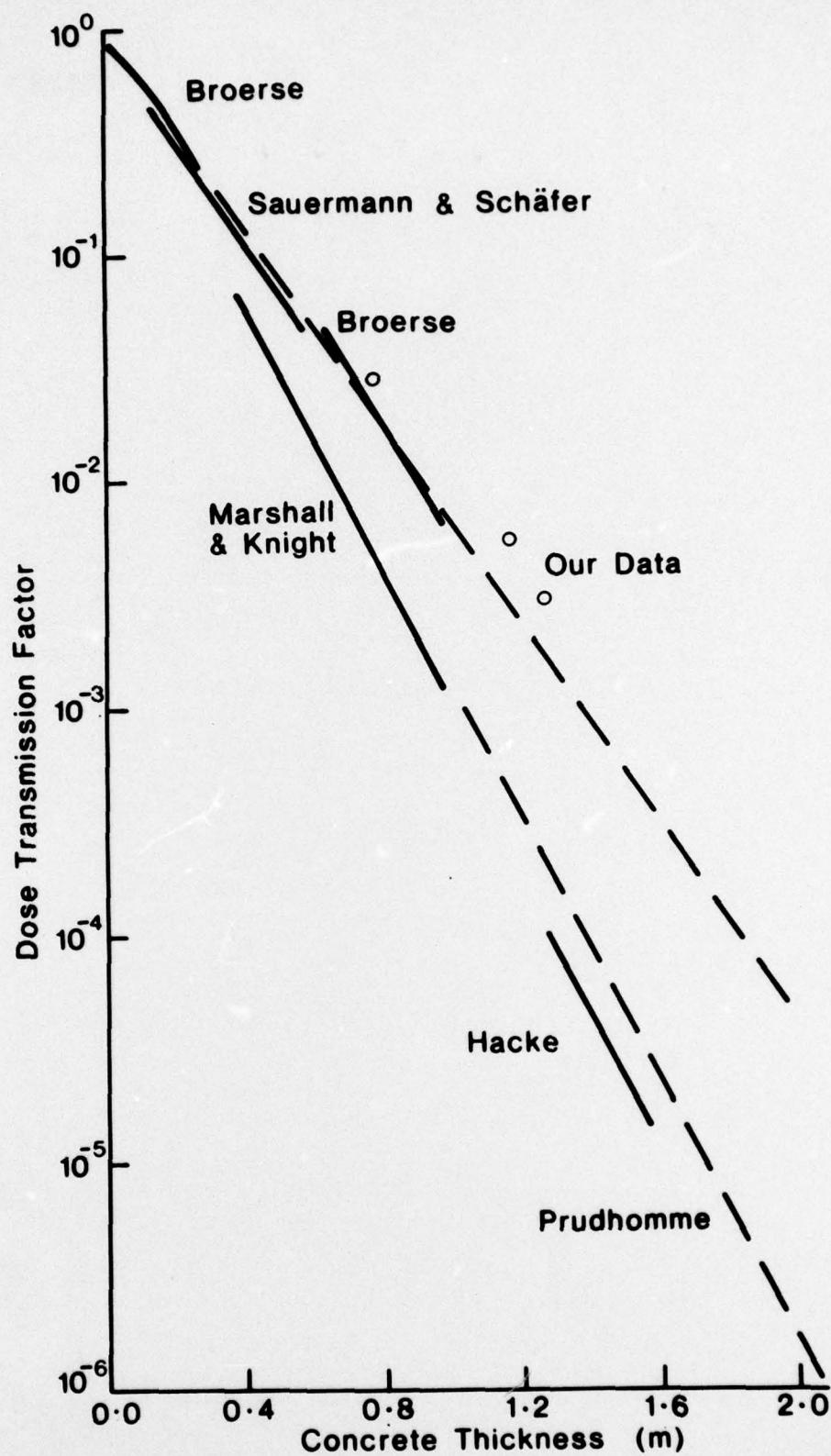


FIG. 2 - Dose transmission for 14 MeV neutrons incident on concrete as a function of concrete thickness.

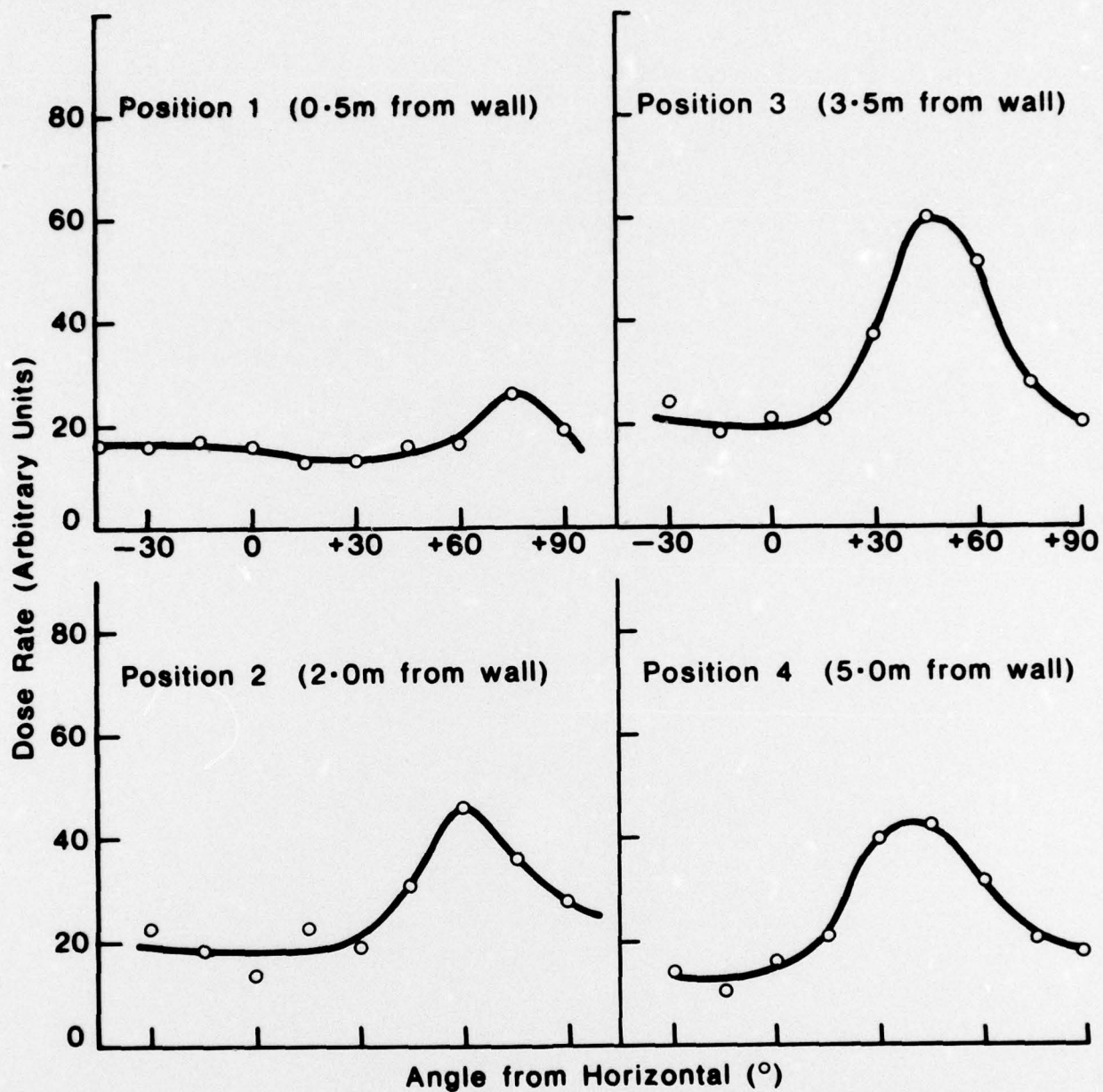


FIG. 3 - Variation of dose rate as a function of collimator angle and distance from the shield wall.

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